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Abstract

Recently, the use of wireless local area networks (WLANs) is extending rapidly as the IEEE 802.11 protocol for medium access control (MAC) and physical layers of WLANs has been standardized. The primary MAC protocol, referred to as distributed coordination function (DCF), is based on carrier sense multiple access with collision avoidance (CSMA/CA). In this paper, we present an analytical model based on a Markov chain for analyzing the performance of a CSMA/CA WLAN under some assumptions. Some discussions about system performance derived from numerical results are given in terms of the throughput and the average packet delay. From the comparison with simulation results, our analytical model is shown to be accurate when the load is light to medium.

Key words: Wireless LAN, IEEE 802.11, MAC protocol, CSMA/CA, Markov Chain, Performance, Simulation

1 Introduction

The technology of wireless LANs (WLANs) is rapidly evolving and becoming common in recent years. This technology provides users with network connectivity without cabling. The impact of wireless communications has been and will continue to be profound. Our interest has been involved in the design of wireless networks for local area. To improve the system performance, several channel access methods have been provided. Among them the IEEE has developed a standard 802.11 for WLANs [1], which is the most prominent specification in the present wireless communication field. In the IEEE 802.11 standard, the medium access control (MAC) and the physical (PHY) layer protocols are specified in detail.

In the IEEE 802.11 protocol, the primary MAC mechanism is referred to as distributed coordination function (DCF). DCF is the fundamental access method used to support asynchronous data transfer, and it is based on carrier sense multiple access with collision avoidance (CSMA/CA). The MAC sublayer is responsible for channel allocation.

Recall that the carrier sense multiple access with collision detection (CSMA/CD) protocol is used in the Ethernet for wired LANs. However, it is difficult to detect collisions in wireless environment where it is not possible to abort transmissions that collide. So it is not appropriate to apply the CSMA/CD protocol to WLANs. The collision avoidance portion of the CSMA/CA is performed to reduce the high probability of collision after a successful transmission by splitting the set of transmitting stations into smaller groups [2].

Our focus in this paper will be on the performance analysis of the CSMA/CA protocol under some assumptions such as no channel errors, a finite number of stations, and no hidden terminal problem. The hidden terminal problem occurs when a single receiving station can hear two transmitters that do not hear each other [3]. In the literature, the performance of the DCF access method has been evaluated by means of simulation [4, 5, 6]. Modeling techniques of WLANs have been proposed for performance evaluation in [7, 8, 9]. In [7], the throughput performance of the DCF is evaluated at the saturation condition. In [8, 9], the non-persistent CSMA/CA protocol with integrated voice and data traffic is analyzed. In these studies, the performance of the CSMA/CA protocol has been evaluated by means of simulation or has been analyzed without taking into account the interaction of each station. An analytical model for non-persistent CSMA protocol for a packet radio network is presented in [10], where a discrete-time Markov process is used to model the system. This is the basis of our analytical model in the present paper.

The rest of this paper is organized as follows. In Sect. 2, the IEEE 802.11 standard and the basic access method of the CSMA/CA are described. After introducing a system model for analysis in Sect. 3, the performance analysis based on a Markov chain is presented in Sect. 4. Section 5 shows numerical results for the throughput and the average packet delay of the system based on the analysis. Section 6 presents the simulation results and discusses the validity of analytical modeling. Concluding remarks are given in Sect. 7.

2 IEEE 802.11 Specification

According to [1], the basic building block of an IEEE 802.11 LAN is called the basic service set (BSS) and an independent BSS (IBSS) is called an ad hoc network. In an ad hoc network, all stations are able to communicate directly. In the specification, two different MAC schemes are supported to transmit asynchronous data and time-bounded data. The first scheme is the distributed coordination function (DCF) designed for asynchronous data transmission. All stations have equally fair chance of transmission in the DCF. Point coordination function (PCF) is the second MAC scheme based on the control of the access point. The PCF is primarily designed for the time-bounded data transmission by using polling. In this paper, we focus on only the DCF scheme and analyze the performance of the DCF.

The basic access method of the DCF is essentially the carrier sense multiple access with collision avoidance (CSMA/CA). The DCF implemented in all stations allows for automatic channel sharing through the use of CSAM/CA along with the random backoff time following a busy channel condition. In addition, all directed traffic uses immediate positive acknowledgement (ACK) frames whereby the retransmission is scheduled by the sender if no ACK is received.

All stations are forced to remain quiet for a certain minimum period, called the interframe space (IFS), after a transmission has been completed. The length of an IFS depends on the type of a frame that the station is about to transmit. High-priority frames like an ACK frame only wait the short IFS (SIFS) period before they contend for the channel. The DCF interframe space (DIFS) is used by the DCF to transmit data packets and the length of a DIFS period is defined by PHY characteristics [11].

The CSMA/CA protocol is designed to reduce the probability of collision by multiple stations accessing the channel. The highest probability of collision exists just after the channel becomes idle following a busy period. This is because multiple stations may have been waiting for the channel to become available. This situation necessitates a random backoff procedure to resolve channel contention conflicts. To avoid simultaneous channel occupation attempts, every station must wait a random backoff time between two consecutive transmissions even if the channel is sensed idle in the DIFS period. The number of consecutive times a station attempts to retransmit a packet is called the backoff stage [1].

In the IEEE 802.11, the time is slotted in time periods corresponding to slot times. The slot time depends on PHY characteristics. It is used to define the IFS interval and backoff times for stations. The random backoff time is an integer value that corresponds to the number of slots and it is distributed according to a uniform distribution (in discrete slot times) where the maximum extent of the uniform range is called the contention window (CW). The CW is an integer within the range of values of PHY characteristics CWmin and CWmax such that CWmin $\leq \mathrm{CW}_i \leq$ CWmax. CW_i represents the ith CW that grows exponentially with i as $\mathrm{CW}_i = 2^{2+i}$, where i indicates the backoff stage.

A station with a packet to transmit senses the channel. If the channel is sensed idle for a DIFS period, the station transmits. Otherwise, if the channel is sensed busy, the station persists to monitor the channel until it is sensed idle for a DIFS period and begins the backoff procedure. To do so, the station sets its backoff counter to a random time. The backoff counter is decremented by one if no channel activity is indicated for the duration of a backoff slot. When it reaches zero, the station transmits its packet. If two or more stations decrement their counters to zero at the same time, the collision occurs and each station renews its backoff time. For retransmission attempts, the backoff time grows as $\lfloor \mathrm{CW}_i * \mathrm{rand}() \rfloor *$ a slot time, where rand() is a uniform random variate in $(0, 1)$, $\lfloor x \rfloor$ represents the largest integer not exceeding x [4].

Figure 1 illustrates the basic CSMA/CA operation. Two stations A and B share the same wireless channel. We assume that station A generates the first packet to transmit at the time indicated with an arrow in the figure. It transmits the packet after a DIFS period. If it has another packet, it sets the backoff counter for transmitting that packet. On the other hand, station B generates the first packet to be transmitted at the time indicated with an arrow in the figure. When station B generates a packet, it senses the channel busy. Station B sets its backoff counter and performs the backoff procedure. After the transmission of packet 1 by station A, both stations A and B wait a DIFS period and then begin to decrement their backoff counters. Say the backoff value for

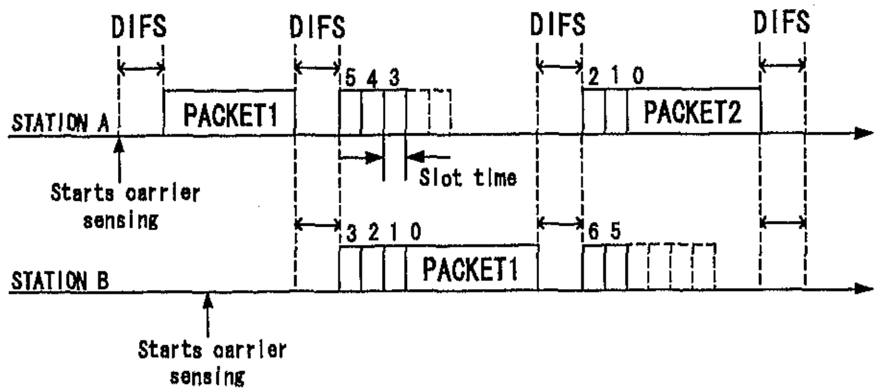

Figure 1: Basic access method of CSMA/CA.

station A equals 5, and that for station B equals 3. Then the backoff counter of station B reaches zero earlier than station A, so station B starts transmission. While the channel is sensed busy by station A, its backoff counter is frozen to 2. It is decremented again only when the channel is sensed idle. Then station A transmits its packet 2.

3 System Model for Analysis

In this section, we present a system model for analyzing the performance of CSMA/CA.

The CSMA/CA is considered here in which the time is slotted with the slot size equal to the propagation delay of radio signals. Each packet is assumed to have fixed length and requires a transmission time of T slots. There are M stations in the IBSS and they can generate packets to communicate with each other. Every station has its own buffer which can store at most one packet at any time. Once a packet is accommodated at a buffer, it remains there until it is successfully transmitted. All stations can start transmission only at the beginning of a slot. If more than one packet are simultaneously transmitted at the same time, a collision occurs. All stations can know the result of transmission by the end of the packet transmission time.

Each station can be in one of two modes: idle mode if it does not have a packet in its buffer to transmit; or backoff mode if it has a packet waiting or undergoing transmission. In the idle mode, a station generates a new packet in a slot with probability σ or remains in the idle mode with probability $1 - \sigma$. A station whose packet either had a collision or was blocked because of a busy channel is said to be in the backoff mode. A station in the backoff mode remains in that mode until it successfully transmits the packet at which time it switches to the idle mode. Thus, a station in the backoff mode cannot generate a new packet for transmission.

In the IEEE 802.11 specification, the backoff interval is uniformly distributed. However, we assume the backoff interval to be geometrically distributed. Each station in the backoff mode attempts to retransmit a packet in a slot with probability ν. The memoryless property of the geometrically distributed retransmission delay will permit simple state description for the mathematical model [10]. For the purpose of this study,

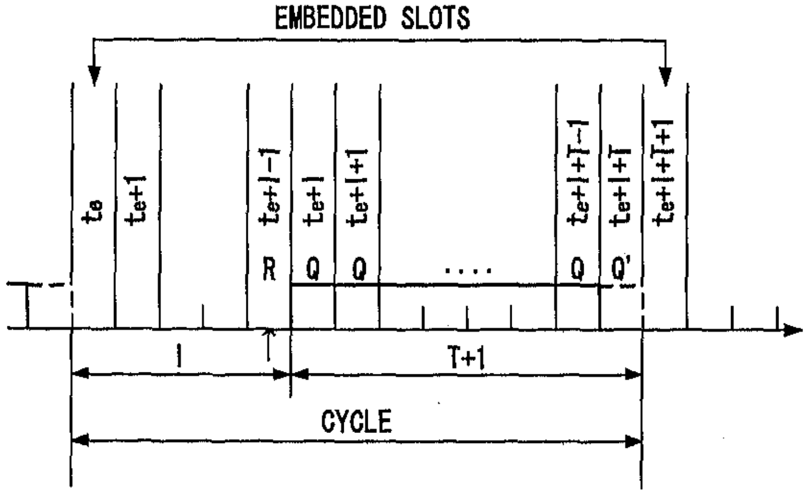

Figure 2: Imbedded slots in a model of CSMA/CA.

we shall assume M, σ, and ν to be time invariant.

Average Retransmission Delay

The average retransmission delay consists of the sum of DIFS periods, the average backoff periods and all other station's packet transmission times before a station finishes the backoff procedure.

In our analytical model, we limit the backoff stage to one for the purpose of simple computation. Since ν is the probability that each station in the backoff mode attempts to retransmit in a slot, the average interval that each station stays in the backoff mode is given by $1/\nu$, where

$$\frac{1}{\nu} = \frac{T}{2} + d + b + M\sigma(d+b)(d+T). \tag{1}$$

Here $T/2$ represents the average interval until the channel becomes idle, d denotes the length of a DIFS period, and $b = 3.5$ is the average backoff counter size. The term $M\sigma(d+b)(d+T)$ accounts for the average packet transmission times of other stations until the backoff counter reaches zero since $M\sigma(d+b)$ is the average number of packets generated during the backoff procedure and $(d+T)$ is a DIFS period plus a packet transmission time.

4 Performance Analysis

In this section, we analyze the system performance based on a Markov chain by following [10]. Figure 2 illustrates a model of CSMA/CA where the time interval in which no stations transmit is called an idle period. The length of an idle period is denoted by I. The first slot of each idle period is defined as an imbedded slot. The time interval between two consecutive imbedded slots is defined as a cycle. Let N^t be a random variable representing the number of stations in the backoff mode in slot t.

In the CSMA/CA, the action taken by a station depends on the state of the channel. For example, those stations in the idle mode generating new packets during a transmission period switch to the backoff mode with probability one. Thus the transition probabilities of the process N^t are not independent of the state of the channel.

State Transition Probabilities

We first consider a cycle and let t_e denote the first slot of the cycle. The system state N^{t_e} denotes the number of stations in the backoff mode at the beginning of a cycle. The length of a cycle is $I + T + 1$. The last one slot is the propagation delay. No stations are ready to transmit a packet during the interval $[t_e, t_e + I - 2]$. However, at least one station becomes ready to transmit in the last slot of the idle period (at time $t_e + I - 1$). For all $t \in [t_e, t_e + I - 1]$ we have $N^t = N^{t_e}$. All stations which become ready at $t_e + I - 1$ attempt to transmit in slot $t_e + I$. Given that $N^{t_e+I-1} = i$, the probability that at least one station is ready to transmit is

$$\Pr\{\text{at least one station is ready} | N^{t_e+I-1} = i\} = 1 - (1-\nu)^i(1-\sigma)^{M-i}. \tag{2}$$

Transmission of some stations starts at slot $t_e + I$. Let $R = (r_{ik})$ be the one-step transition matrix from slot $t_e + I - 1$ to $t_e + I$ defined by

$$r_{ik} \triangleq \Pr\{N^{t_e+I} = k | N^{t_e+I-1} = i\}. \tag{3}$$

For $i = 0, 1, 2, \ldots$, it is given by

$$r_{ik} = \begin{cases} 0, & k < i \\ \dfrac{(1-\sigma)^{M-i}[1-(1-\nu)^i]}{1-(1-\nu)^i(1-\sigma)^{M-i}}, & k = i \\ \dfrac{\binom{M-i}{k-i}(1-\sigma)^{M-k}\sigma^{k-i}}{1-(1-\nu)^i(1-\sigma)^{M-i}}, & k > i. \end{cases} \tag{4}$$

All idle stations generating new packets will be blocked from transmission during the transmission interval $[t_e + I, t_e + I + T]$ in which the channel is busy. These stations switch to the backoff mode. For any $t \in [t_e + I + 1, t_e + I + T]$, let $Q = (q_{ik})$ be the one-step transition matrix defined by

$$q_{ik} \triangleq \Pr\{N^t = k | N^{t-1} = i\}. \tag{5}$$

For $i = 0, 1, 2, \dots$, we have

$$q_{ik} = \begin{cases} 0, & k < i \\ \binom{M-i}{k-i}(1-\sigma)^{M-k}\sigma^{k-i}, & k \geq i. \end{cases} \tag{6}$$

with the convention that $\binom{M}{k} = 0$ for $k > M$.

Finally, we define $Q' = (q'_{ik})$ to be the one-step transition matrix corresponding to the last slot of the cycle

$$q'_{ik} \triangleq \Pr\{N^{t_e+I+T+1} = k | N^{t_e+I+T} = i\}. \tag{7}$$

There exist two types of events in the last slot: (1) if the number of transmitting stations is one, that transmission is successful and the corresponding station switches to the idle mode; (2) stations that are in the idle mode and ready in the last slot will still sense the channel busy at that slot and switch to the backoff mode. The probability of success over the transmission period depends on the state of the system at the time the transmission begins, i.e., on N^{t_e+I-1} which statistically equals N^{t_e}. Conditioned on $N^{t_e} = n$, the probability of success, denoted by $P_s(n)$, is given by

$$P_s(n) = \frac{(1-\nu)^n(M-n)\sigma(1-\sigma)^{M-n-1} + n\nu(1-\nu)^{n-1}(1-\sigma)^{M-n}}{1-(1-\nu)^n(1-\sigma)^{M-n}}. \tag{8}$$

The transition probabilities in the last slot therefore also depend on N^{t_e}. For $j = 1, 2, \dots, M$, they are given by

$$q'_{jk}(n) = \begin{cases} 0, & k < j-1 \\ (1-\sigma)^{M-j}P_s(n), & k = j-1 \\ (M-j)\sigma(1-\sigma)^{M-j-1}P_s(n) & \\ \quad +(1-\sigma)^{M-j}[1-P_s(n)], & k = j \\ \binom{M-j}{k-j}\sigma^{k-j}(1-\sigma)^{M-k}[1-P_s(n)] & \\ \quad +\binom{M-j}{k-j+1}\sigma^{k-j+1}(1-\sigma)^{M-k-1}P_s(n), & k > j. \end{cases} \tag{9}$$

Imbedded Markov Chain

Next, we focus on the state of the system at the imbedded slots defined above. Clearly, N^{t_e} constitutes an imbedded Markov chain. The discrete state space of the Markov chain consists of the integers $\{0, 1, 2, \dots, M\}$. Its transition matrix $P = (p_{nk})$ is defined by

$$p_{nk} \triangleq \Pr\{N^{t_e+I+T+1} = k | N^{t_e} = n\}. \tag{10}$$

To compute P, we first obtain the matrix $P' = (p'_{nj})$ defined by

$$p'_{nj} \triangleq \Pr\{N^{t_e+I+T} = j | N^{t_e} = n\}. \tag{11}$$

Clearly, P' is given by

$$P' = RQ^T, \tag{12}$$

where Q^T is the Tth power of the matrix Q. The matrix P is then computed by

$$p_{nk} = \sum_{j=n}^{M} p'_{nj} q'_{jk}(n). \tag{13}$$

From a practical point of view, P can be more easily computed from matrix $P'' = (p''_{ij}) = RQ^{T+1}$ by the following simple transformation:

$$p_{nk} = p''_{nk}[1 - P_s(n)] + p''_{n,k+1} P_s(n). \tag{14}$$

Given M, σ and ν, the finite state imbedded Markov chain is ergodic and a stationary probability distribution $\Pi = \{\pi_0, \dots, \pi_j, \dots, \pi_M\}$ exists. It is computed by the equations

$$\Pi = \Pi P \quad ; \quad \sum_{j=0}^{M} \pi_j = 1. \tag{15}$$

Average Idle Period

Let $\eta_k(i) \triangleq \Pr\{I = k | N^{t_e} = i\}$ be the probability that the length of an idle period is k under the condition that $N^{t_e} = i$. Given $N^t = i$, the probability that no terminals become ready in slot t is given by $\delta_i = (1-\nu)^i(1-\sigma)^{M-i}$. Since the state of the system remains unchanged during the idle period, we have the geometric distribution

$$\eta_k(i) = (1-\delta_i)\delta_i^{k-1} \qquad k = 1, 2, \dots. \tag{16}$$

Thus, given $N^{t_e} = i$, the average length of an idle period is $1/(1-\delta_i)$.

Average Number of Backoff Stations

Let $\overline{N}$ represent the average number of stations in the backoff mode. It is given by

$$\overline{N} = \frac{\sum_{i=0}^{M} \pi_i \left[\frac{1}{1-\delta_i} i + A(i) \right]}{\sum_{i=0}^{M} \pi_i \left[\frac{1}{1-\delta_i} + T + 1 \right]}, \tag{17}$$

where

$$A(i) = \sum_{m=0}^{T} \sum_{j=i}^{\min(M, i+m+1)} j s_{ij}^{(m)}, \tag{18}$$

and $s_{ij}^{(m)}$ is the (i, j)th element of matrix $S^{(m)}$ defined by

$$S^{(m)} \triangleq RQ^m, \qquad 0 \leq m \leq T. \tag{19}$$

The derivation of Eq. (17) is given in [10].

Throughput

The normalized system throughput S is defined as the average number of successful packet transmissions per T slots. It is given by

$$S = \frac{\sum_{i=0}^{M} \pi_i T P_s(i)}{\sum_{i=0}^{M} \pi_i \left[\frac{1}{1-\delta_i} + T + 1 \right]}. \tag{20}$$

Average Packet Delay

By Little's law, the average packet delay is simply expressed as

$$D = \frac{\overline{N}}{S}. \tag{21}$$

This is normalized by the packet transmission time T.

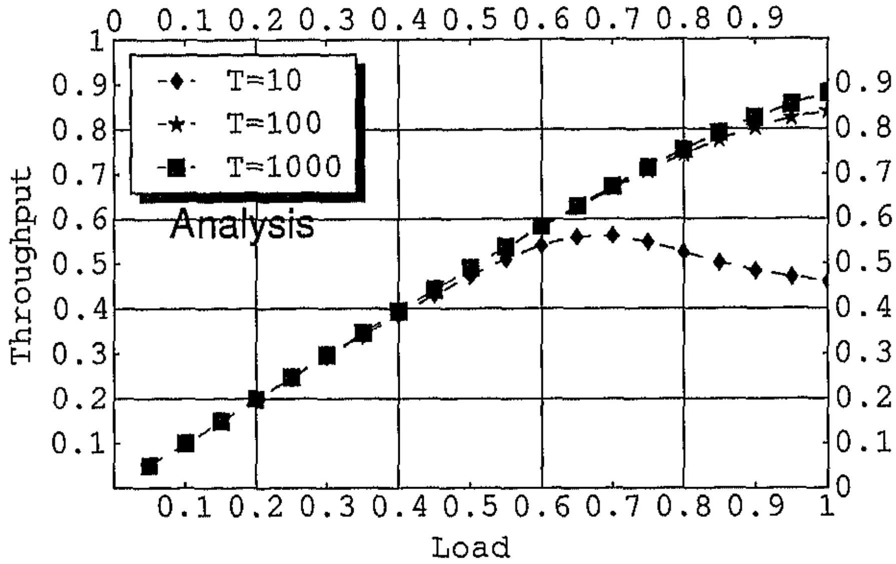

Figure 3: Throughput versus load by analysis ($M = 50$).

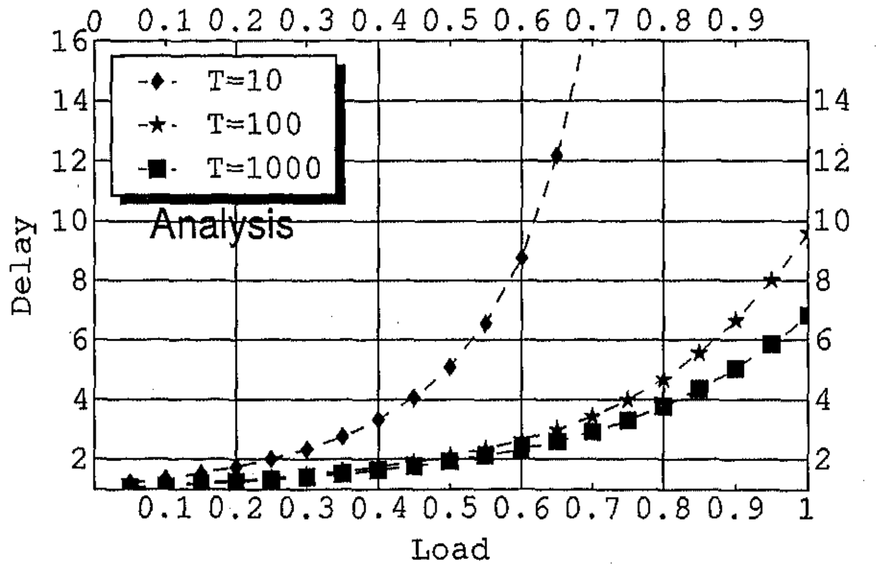

Figure 4: Average packet delay versus load by analysis ($M = 50$).

5 Numerical Results

In this section, we show some numerical results, based on the above analytical model, for the throughput and the average packet delay under the following conditions:

- The length of a DIFS period is 5 slots ($d = 5$).
- The system consists of 50 stations ($M = 50$).
- The backoff stage is limited to 1.

The limit of the backoff stage is reasonable when the load is light to medium where few collisions occur. The load ($M\sigma T$) represents the average total transmission times of new packets generated in the whole system during a packet transmission time.

Figure 3 shows the throughput versus load plot for various values of T. It is seen that the throughput increases linearly when the load is light to medium and then levels off as the load becomes heavy. The throughput increases linearly at the light load since most stations that generate new packets sense the channel idle and are able to begin transmission immediately without collision. As the system becomes saturated at the heavy load, the throughput remains at the same value and then decreases gradually. The same situation has been observed in the previous simulation study [4, 6]. We note that by decreasing the packet length T the maximum throughput decreases. The reason is that the overhead of the backoff procedure affects the throughput largely when the packet is short.

In Fig. 4, we plot the average packet delay for various values of T. In this figure, when $T = 100$ and the load is close to 0 where stations can begin to transmit immediately, the average packet delay tends to 1.05 in the unit of T, which is a packet transmission time plus a DIFS period. When the load is greater than the value at which the maximum throughput is achieved, the average packet delay increases rapidly. As is the case with the throughput, the shorter the packet transmission time is, the larger the average packet delay becomes because of the overhead of backoff procedure.

6 Simulation

In this section, we present a simulation model and compare the result with the analytical model.

6.1 Assumptions for Simulation

The following assumptions have been made in the simulation model.

- The population of stations in the IBSS consists of M stations.
- The wireless channel is shared by all stations in the IBSS. The access method is based on the DCF.
- The slot size of time equals to the signal propagation delay.

- The packet transmission time T is fixed.
- The generation of packets at each station follows a Poisson process.
- Each station has a buffer that is able to store at most one packet. If a new packet is generated at the station when the buffer is occupied, that packet is discarded.
- If two or more stations transmit packets simultaneously, a collision occurs and the retransmission follows according to the backoff procedure.
- The number of retransmission attempts is not limited.
- The hidden terminal problem is not addressed.

We evaluate the system performance in terms of the throughput and the average packet delay. Definitions of the throughput, the average packet delay and the load are the same as for the analytical model.

There are two main assumptions that are different between the simulation model and the analytical model in this paper. First, the maximum backoff stage is set to 6 in the simulation model while it was set to one in the analytical model. Second, the packet interarrival times are exponentially distributed in the simulation model while they were geometrically distributed in the analytical model.

For the purpose of the comparison with the analytical results, some simulation assumptions described above are different from the real system such as a unit buffer size and the fixed packet transmission time. We neglect channel errors, use of ACK frames, and the fragmentation of packets.

6.2 Results

To compare the results of the simulation with that of the analysis, we use the same parameter values for the simulation as those used in the analytical model for the DIFS period and the number of the stations ($d = 5$ slots and $M = 50$ stations). Each simulation run is carried out until $10,000$ packets are processed.

In Fig. 5, we can see the effect of the packet transmission time T on the throughput. The longer the packet transmission time is, the more efficient the system becomes. However, when the packet transmission time is greater than 100 slots, the increase in the maximum throughput value becomes marginal.

Figure 6 shows the effect of the packet transmission time T on the average packet delay. The heavier the load becomes, the average packet delay increases at higher pace. The average packet delay for $T = 100$ slots closely resembles that for $T = 1000$ slots.

6.3 Validation of Analytical Model

Let us discuss the validity of our analytical modeling by comparing the results of the analysis with that of the simulation. In Figs. 7 and 8, the simulation results are plotted with dashed lines, where applicable, with 95 percent confidence intervals and the analytical results are plotted with continuous lines.

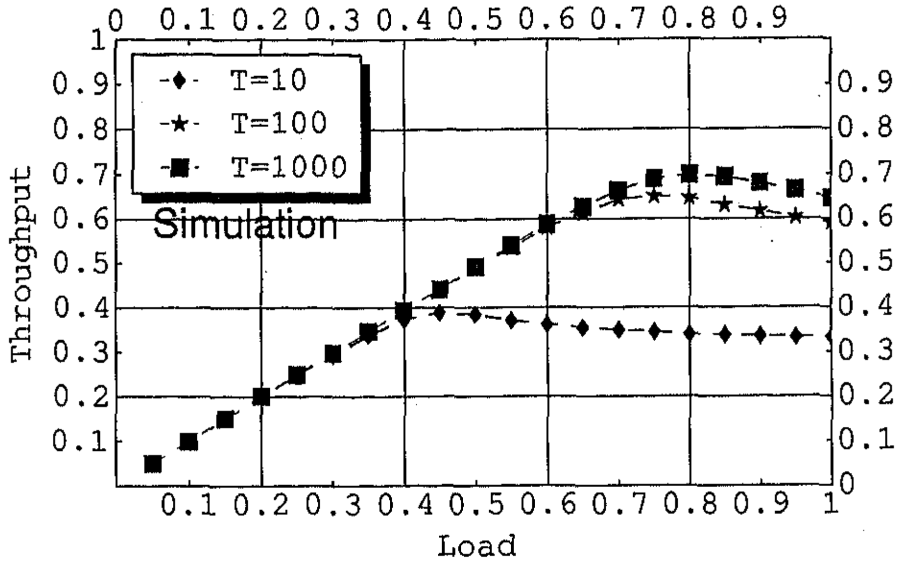

Figure 5: Throughput versus load by simulation ($M = 50$).

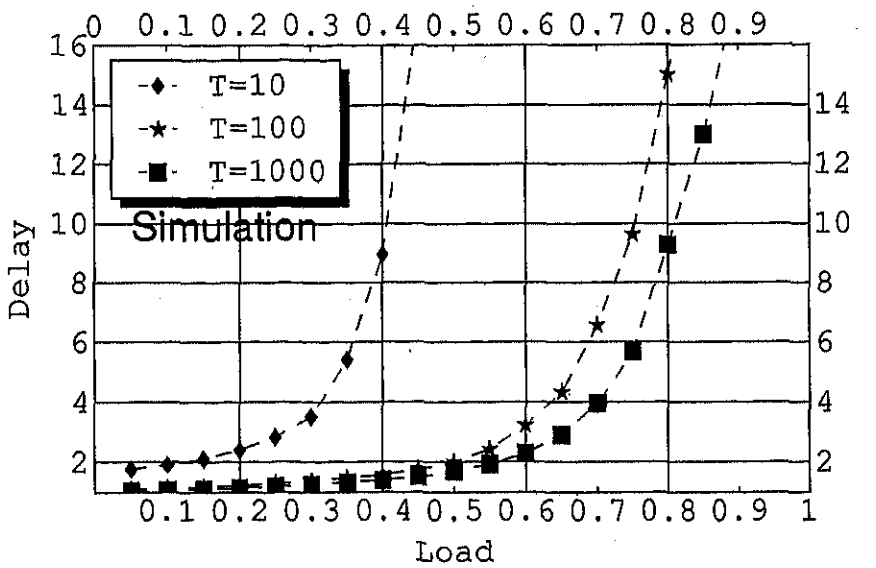

Figure 6: Average packet delay versus load by simulation ($M = 50$).

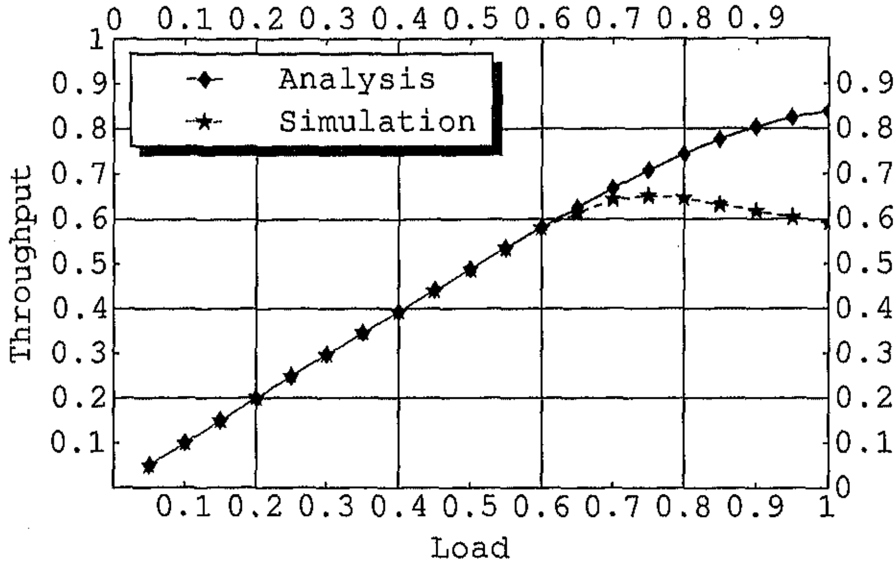

Figure 7: Throughput versus load ($T = 100, M = 50$).

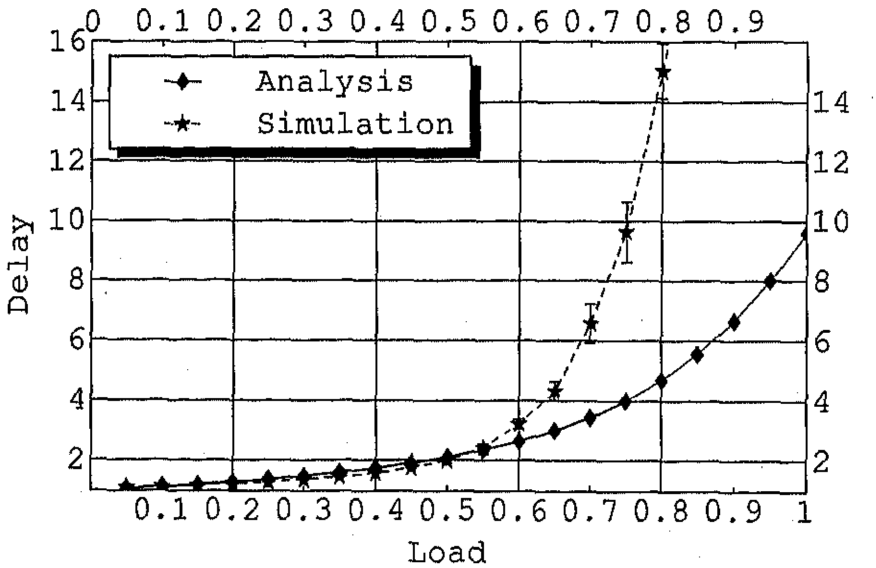

Figure 8: Average packet delay versus load ($T = 100, M = 50$).

From Figs. 7 and 8, we can say that our model is approximately accurate at the light to medium load (when the load is less than about 0.6). In our analytical model, we have assumed that the maximum backoff stage is one. On the other hand, the maximum backoff stage is set to 6 in the simulation model to reflect realistic operation described in the specification. When the load is greater than 0.6, the average number of collisions of each packet exceeds one and the backoff stage switches to the second and further stages in most stations. This is the reason why the analytical results do not match the simulation in heavily loaded conditions.

7 Conclusion

In this paper, we have presented an analytical model based on a Markov chain for the CSMA/CA protocol under some assumptions. We have given some numerical results for the throughput and the average packet delay to analyze the performance of the system. The throughput is improved and the average packet delay is shortened when the packet transmission time is long. This is due to the low overhead of the backoff procedure.

We have also compared the analytical results with simulation to validate our analytical model. Our model is approximately accurate when the load is light to medium. However, when the load is heavy so that collisions of packets tend to repeat, our model deviates from the real system because we do not take into consideration the case in which the backoff stage exceeds one. We need to eliminate this limitation as well as other simplifying assumptions to propose a more accurate analytical model for the CSMA/CA protocol.

References

[1] IEEE standard for wireless LAN medium access control (MAC) and physical layer (PHY) specifications, 1999.

[2] B. Bing, "High-speed wireless ATM and LANs," Boston: Artech House, 2000.

[3] R. O. LaMaire, A. Krishna, P. Bhagwat, and J. Panian, "Wireless LANs and mobile networking: standards and future directions," IEEE Communications Magazine, vol.34, no.8, pp.86–94, August 1996.

[4] B. P. Crow, I. Widjaja, J. G. Kim, and P. T. Sakai, "IEEE 802.11 wireless local area networks," IEEE Communications Magazine, vol.35, no.9, pp.116–126, 1997.

[5] A. Heindl and R. German, "Performance modeling of IEEE 802.11 wireless LANs with stochastic Petri nets," Performance Evaluation, vol.44, issue 1–4, pp.139–164, 2001.

[6] J. Weinmiller, M. Schlager, A. Festag, and A. Wolisz, "Performance study of access control in wireless LANs IEEE 802.11 DFWMAC and ETSI RES 10 HIPERLAN," Mobile Networks and Applications, vol.2, pp.55–67, 1997.

[7] G. Bianchi, "Performance analysis of the IEEE 802.11 distributed coordination function," IEEE Journal on Selected Areas in Communications, vol.18, no.3, pp.535–547, March 2000.

[8] W. Yue and Y. Matsumoto, "A new effective analysis for wireless CSMA/CA LANs supporting real-time voice and data services," IEICE Transactions on Fundamentals of Electronics, Communications and Computer Sciences, vol.E84-A, no.7, pp.1660–1669, July 2001.

[9] W. Yue and Y. Matsumoto, "Performance Analysis of Multi-Channel and Multi-Traffic on Wireless Communication Networks," Kluwer Academic Publishers, 2002.

[10] F. Tobagi and L. Kleinrock, "Packet switching in radio channels: Part IV — stability considerations and dynamic control in carrier sense multiple access," IEEE Transactions on Communications, vol.COM-25, no.10, pp.1103–1119, October 1977.

[11] A. Leon-Garcia, I. Widjaja, "Communication Networks," McGraw-Hill, 2000.